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30 September 1996

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Hon. Reed E. Hundt, Chairman
Federal Communications Commission
1919 M. St.
Washington DC 20554

MM Docket 87-268

Dear Mr. Chairman:

The attached Additional Reply Comments to the Fifth NPRM deal with the Reply Comments of North American Philips and ATSC. I request that they be made a part of the record in this docket.

The Philips Comments contain many incorrect statements about the relative merits of interlace and progressive transmission, and are bound to be confusing in the search for an optimum standard for digital TV transmission in the US. Although I have dealt with most of these errors in previous submissions, I felt it was important to rebut them once again, in an effort to provide an accurate and complete record that the Commission can use in coming to a decision.

The ATSC Reply Comments (which are substantially identical to those submitted by the Grand Alliance) go much further. In addition to similar incorrect statements as in the Philips submission, they offer highly inaccurate and misleading information about my own submissions. Nearly every reference to any of my own statements misrepresents what I said. My reputation for accuracy and clear thinking is very important to me, and I felt there was no choice but to respond.

Interlace is obsolete. Unfortunately, some companies have made an unwise investment in this technology and are now trying to foist it off on the Commission, on consumers, and on domestic industry. I hope the Commission does not yield to this pressure. Interlaced transmission has no place in any new television broadcasting system.

Very truly yours,

William F. Schreiber

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Before the Federal Communications Commission
Washington DC 20554

In the Matter of
Advanced Television Systems
and Their Impact upon the
Existing Television Broadcast Service

MM Docket 87-268
Fifth Further Notice of Proposed Rule Making

Additional Reply Comments of

William F. Schreiber
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Research Laboratory of Electronics
Massachusetts Institute of Technology

Submitted 30 September 1996

The opinions in these comments are those of the author only.
He has no financial dealings with any computer company.
Since his retirement in 1990, the author has had no role in
directing MIT's Advanced Television Research Program.

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Executive Summary

In its Reply Comments to the Fifth NPRM, North American Philips makes a number of incorrect statements about the alleged advantages of interlaced transmission, such as that 1080 lines interlaced makes better pictures than 720 lines progressive. (This assertion was shown to be untrue in ATTC tests.) In my previous submissions, I dealt thoroughly with this and every other such assertion, showing that all are wrong. Continuing to advance such fallacious ideas in the face of clear contrary evidence does not make a constructive contribution to dealing with the issues now up for decision by the Commission. I have once again, but briefly, presented the main evidence.

ATSC and the Grand Alliance go far beyond advancing faulty arguments. They have seriously misrepresented my submissions. In the section on the interlace/progressive issue, nearly every reference to the various documents I have submitted is incorrect and/or misleading. In particular, they have falsely charged that the papers by other authors that I submitted in support of my position do not in fact do so, and may even advance a contrary conclusion. In this paper, I have tried to set the record straight.

Interlace is obsolete. Some companies have unwisely invested in this technology and are now trying to foist it off on the the Commission, consumers, and the rest of the industry. My view, which has only been strengthened by these attacks, is that American stakeholders will be better off immediately, and everyone will be better off in the long run, even including those companies now pushing interlace, if progressive transmission only is included in the upcoming standard.

1. Introduction

In my submissions of 11 March, 14 June, and 10 July of this year, I dealt with the progressive/interlace issue at length, using mostly objective criteria. I also examined the economic issues and concluded that there is no advantage, economic or otherwise, to any domestic stake-holder in using interlaced transmission. While there is a temporary advantage from interlaced transmission for manufacturers of 1125-line interlaced studio equipment, I believe they would also benefit in the long run from using progressive transmission from the outset as we make the momentous change to digital TV. The reasoning here is that progressive transmission will permit higher quality, a faster transition away from NTSC, and more rapid growth of the industry. I have therefore urged the Commission to permit only progressive transmission formats in the standard about to be adopted.

Not surprisingly, I have not succeeded in convincing everyone on these points. In their responses, some (such as Philips) repeat many of the same incorrect "facts" that I had hoped to dispose of earlier. In this note, I try once more to get the facts on the table. ATSC (and the Grand Alliance) have extensively misrepresented my statements to a degree that demands a response.

I wrote privately to individuals at Philips (30 August) and at ATSC (4 August) who, I believe, are fully competent to understand the technical points that are mentioned below, hoping to get a response from them before submitting this document. Unfortunately, neither responded. If they do so at some later time, and if any modification in what I have said is called for, then I shall write to the Commission again.

2. Reply Comments of ATSC and the Grand Alliance

The discussions of the progressive/interlace issue in these two sets of comments are nearly identical, indicating that they came from the same source. In what follows, I have used the page numbers in the ATSC version.

In Section B of the submission, Progressive vs Interlaced Scanning, a number of mistatements are made about my Comments on the Fifth NPRM, submitted 14 June 1996, in particular as to whether the papers in the Appendix actually support my contention to the effect that P signals of twice the analog bandwidth can be compressed to the same digital date rate as I pictures. In what follows, I show that each paper does in fact fully support my conclusion. Please note that my recommendations to the Commission about interlace do not depend solely on the higher compressibility of progressively scanned video, important though that is. There is plenty of other evidence that P is always better than I. (See my note of 21 August in the Appendix.)

2.1. The Petajan Paper (Bell Labs)

Petajan compared the codability of an I signal that was obtained from a P signal by taking odd lines from one frame and even lines from the next. (From talking with Dr. Petajan, I believe the P video was vertically filtered to have the same apparent vertical resolution as the I video.) Both were encoded to the same digital data rate. The subjective quality of the decoded P picture was generally *higher* than that of the I picture. On page 6: "Since the pixel rate of the progressive format is twice that of the interlaced format, the coding efficiency has been shown to be twice that of interlaced scanning." The only exception was signals with excessive noise, as would be expected.[1]

2.2. The Pigeon and Guillotel paper (R2110/WP2/DS/R/004/b1)

On p 27: "...The 50-Hz progressive format may be coded using the same *bit* rate as interlaced at same or improved quality." The authors rely on several of the references in their paper for proof of this statement.

2.2a. A later paper by the same authors. "Coding Efficiency Comparisons of both Interlaced and Progressive Scanning Formats" (RACE/HAMLET R2110/WP2/DS/R/012/b1) This paper was appended to the second part of my Comments, submitted 10 July 1996.

Both of these papers report work on the HAMLET project, funded by the European Union under the RACE program, and organized by CCETT, a French government research and educational institution. Mlle Christine Guillemot was the coordinator at CCETT. The project was in operation for two years beginning January 1994. There were 12 full partners in the consortium that carried out the work. M. Pigeon is with the Telecommunications and Teledetection Laboratory of the Catholic University in Louvain-La-Neuve, Belgium, and M. Guillotel is with the Thomson Multimedia R&D Lab in France. In a recent communication, Pigeon has confirmed my interpretation of these papers and has also provided a final Recommendation from the project which is appended to this submission.

This is the most complete study of the issue ever made, as far as I know. Figure 8 from the paper is shown on the next page. All combinations of progressive and interlaced (P and I) sources, transmission, and display were studied. The images were 576x720x50 fields/sec, at coded data rates of 2, 4, and 6 Mb/s, *the same data rate being used for all combinations.*[2] (This covers the conditions that would be used in both HDTV and SDTV.) From the Conclusion: "At the *same bit-rate,* (my emphasis) an all-progressive broadcasting chain, from the source capture to the final display, is thus preferable to an all-interlaced one, except for increased hardware complexity since twice the number of pixels is scanned.....the higher the sequence complexity, the bigger the improvement is....." This paper thus confirms the conclusions of the other papers listed here.

2.3. The Muratori, Stroppiana, and Nishida paper (RAI and NHK)

In this paper, the I signals were obtained from P signals as in the Petajan paper. Vertical filtering was used to make their resolutions equal. On page 6: "...The bit-rate required by the vertically filtered progressive pictures is about equal to that necessary for the interlaced picture..." In this

[1]The higher compressibility of progressive video is due to its higher spatiotemporal correlation. Noise reduces such correlation. Pure noise is uncorrelated and cannot be compressed at all.

[2]The effect of the various bit rates was only studied for one combination, but there is no reason to believe it would be different for other combinations.

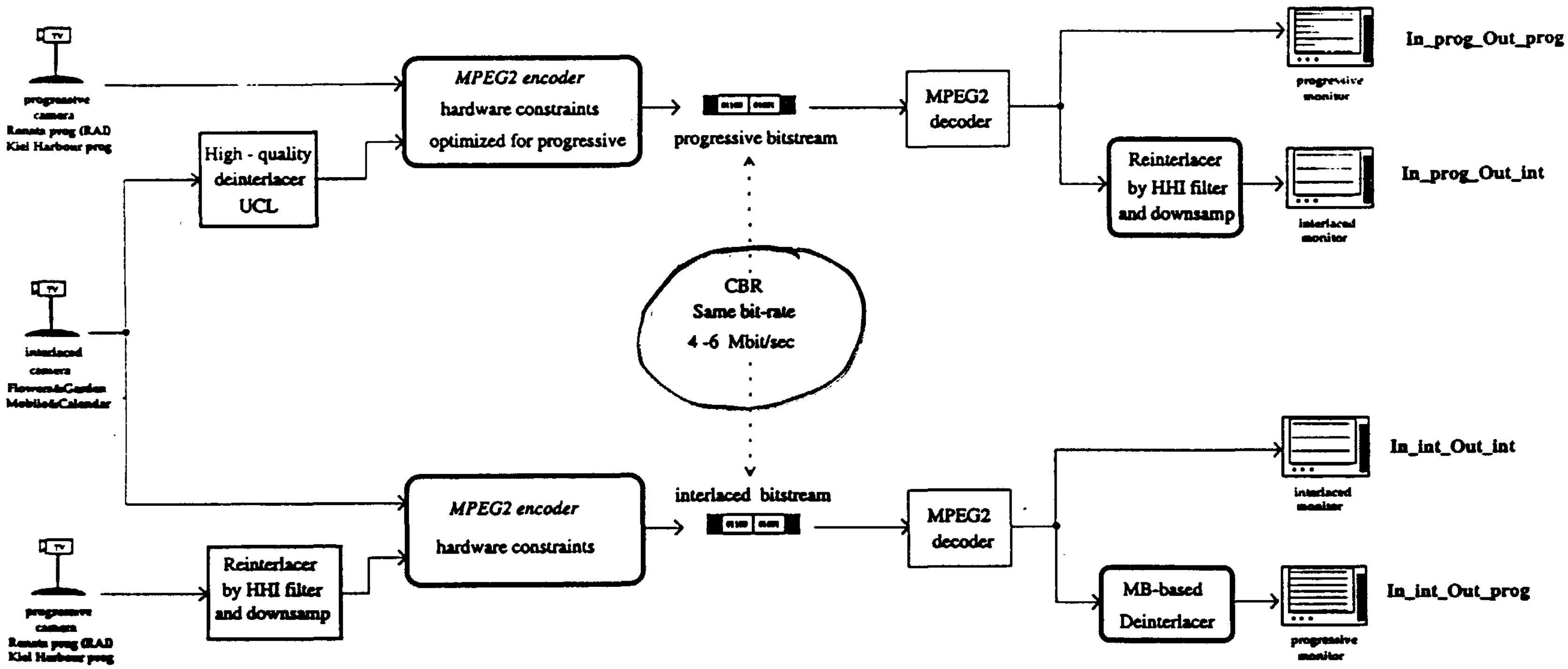

Fig. 8 - Interlaced and Progressive transmission formats

Figure 8 From the Pigeon et al paper.

experiment, the two rates were about equal at .5 bits/pel, while the P rate was *lower* than the I rate at fewer bits/pel, which would be the case in the ATSC system. The subjective quality was about the same. On page 8: "...the de-interlaced pictures can be coded with the improved coding scheme, and at low bit-rates, with the same amount of bit (sic) of the interlaced ones, even though they have a double number of samples."

2.4. NHK/RAI paper CCIR Doc. TG CMTT/2-SRG-088

The same method as above was used to obtain an I signal from a P signal of twice the bandwidth. The same conclusion was drawn as above: the P signal can be coded at about the same data rate and the same quality at coding efficiencies of .5 bits/pel or lower, as would be used in the ATSC system.

I think it is clear that these papers do indeed support my statement. It is worth noting that all the labs doing this work have good reputations. The European work has been going on for several years. If it was defective in any way, interlace advocates would long since have said something about it.

There are a number of other points in the ATSC Reply Comments that are incorrect.

On page 46, it is stated that my concern about the danger to nondisruptive improvement over time from interlaced transmission "does not bear scrutiny," without giving any substantiation, except to talk about headers and descriptors. Headers and descriptors, an MIT contribution to the Inquiry, are valuable, but have absolutely nothing to do with the I/P issue. They simply tell the receiver what is coming. They do not affect coding efficiency or the difficulty of transcoding. In my various submissions, I have gone into considerable detail as to why I have this concern.

On page 49, I am said to ignore the alleged higher horizontal resolution of the interlaced system. The measurements made by ATTC (p 3 of the ATTC Final Report) are suspect because the dynamic horizontal resolution of the I system was measured at 500 c/aph while the target value was 345. These values were 300 and 230 for the P system. There is no reason why the ratio of these numbers should be different in the two systems. Therefore, I doubt that the I system did really have much higher horizontal resolution. This suspicion is borne out by the fact that the subjective quality of the two was about equal. If the I system did have anywhere near twice the resolution elements per frame as the P system, one would think the observers would notice it. (It would also have required a higher coded data rate to render the higher resolution.) The key fact here is that the measured dynamic vertical resolution of the P system was a little *higher* than that of the I system, in spite of only having 67% as many lines/frame. The dynamic chroma resolution, both vertical and horizontal, of the P system was *much* higher than that of the I system. So much for the oft-stated assertion about 1080 I being "true" HDTV while 720 P is not.

On page 50, I am said to admit that my claim about the relative compressibility of I and P signals was not true because I had referred to a multiresolution system that my students and I have simulated that transmits a higher data rate at higher SNR. I made no such admission at all. The multiresolution approach referred to is a good way, I think, to utilize the higher Shannon rate closer in (channel capacity that is not utilized at all in the ATSC system) to get better pictures. My statement about double compression being available with progressive transmission does not depend on this factor at all, as even a cursory reading of my submission would show.

3. Reply Comments of North American Philips

Last month, I received errata sheets for the Philips Reply Comments of 12 August, together with an apology for referring to me as "CICATS' principal economic advisor." Although I was happy to have the error corrected, it was an odd error to have made, since it plainly says on the cover sheet of my Comments that I have no financial dealings with any computer company. No one is paying me to make submissions to the FCC in this case.

After receiving the correction, I called and asked for the entire Philips submission. (The erroneous statements were still in the copy I received.) I was surprised at the number of outright technical mistatements, particularly coming from a well regarded research laboratory. What is principally at issue is the question of interlace vs progressive scan, on which my position is very clear.

The Philips paper asserts that only the computer companies in CICATS are against interlace. I am sure this is not true. As far as I know, virtually all computer interests are against interlace. Among broadcasters, ABC and Fox are in favor of progressive. (To get some idea of what Fox thinks about this issue, refer to the 9/66 J. SMPTE.) The charge is also made that computer companies are taking this position out of regard for their own financial interest. I take it for granted that computer companies are acting in their perceived self-interest, but so is Sony and most other companies that hope to make money in ATV. I presume Philips is, as well. This is all to be expected and is perfectly proper.

The material on page 12 and elsewhere concerning the relative performance of I and P systems is totally incorrect. I is not better than P for sports, as some are contending. The 1080 I format does not produce better pictures than the 720 P format, according to the tests performed at ATTC. In fact, the measured vertical resolution of the latter was higher than that of the former, and the subjective quality was about the same. Although the ATTC tests did not measure it directly, there is no doubt at all that 60 fps P must give better motion rendition than 30 fps I. The Norwegian paper accompanying my note of 21 August (in the Appendix) concludes that, using properly optimized MPEG-2 coding at the same data rate, a 576x1024x50 P picture is subjectively superior to 1152x1024x 25 I. The various papers from Bell Labs, Project RACE/HAMLET, NHK, and RAI, submitted with my earlier comments show that, *coded at the same data rate,* an I signal and a P signal with the same number of lines per frame and fields per second (so that the P signal has twice the analog bandwidth of the I signal) have about the same quality for static pictures. With these experimental facts available, how can anyone still want to use interlace? Of course, interlaced displays can still be used in cheaper receivers, since the required P-to-I conversion, including the necessary vertical low-pass filtering, is very simple, whereas good I-to-P conversion is costly.

On page 16, the Broadcasters' Comments are quoted to the effect that only interlace gives 1000 lines resolution at 60 Hz. This is also incorrect. The vertical definition of interlaced systems must be not much more than half the number of lines per frame in order to avoid intolerable interline flicker. *As conclusively shown by the ATTC tests, 1080 I does not give higher vertical resolution or better quality than 720 P.* I have seen many 1125 I demonstrations and never did the limiting vertical resolution exceed about 700 lines. Contrary to the Philips statement, progressive scan has already advanced to the point where it can provide comparable static (and better dynamic) performance than P.

On page 17, the statement is made (quoting ATSC) that interlaced scanning will permit more NTSC-quality programs to be transmitted in a single channel than progressive. This is also untrue. Several of my former students who previously worked on the GI system have formed a company called Imedia to perform this very function. At NAB they demonstrated 24 programs in one channel. As input, they used NTSC signals derived from film at 24 fps by the 3-2 pulldown method. The first step in their process was to go back to the 24 P format, converting to the 30 I format after decoding. Dr. Ed. Krause of Imedia (415 975 8000) tells me that for camera-derived NTSC, they can usually do 18 programs and for very fast action, again from a camera, they can do 12 programs in one channel. Since this is likely to be a very popular mode of transmission, these results are of great importance.

4. Conclusion

The Philips arguments for using interlaced transmission, viz: only a few computer companies are against interlace, 1080 I gives better pictures than 720 P, only interlace gives 1000 lines vertical definition at 60 fps, and that interlace permits more SDTV programs to be transmitted in a single channel, are all incorrect. Every one of these assertions is untrue.

ATSC makes many of the same erroneous statements as Philips. In addition, ATSC has gravely misrepresented my submissions. Virtually every point made about what I said is wrong, and can easily be shown to be wrong. In particular, the attempt by ATSC to show that the papers that I submitted do not support my views illustrates the total absence of validity in their criticism. One would think that, if interlace really had some virtues, it would be possible to make the case without resorting to such tactics.

Interlaced transmission conveys no long-term advantage of any kind to anyone and only a temporary advantage to companies that have made unwise investments in this obsolete technology. There are many hazards to permitting interlaced broadcasting, not the least of which is the difficulties it will place in the way of making nondisruptive improvements over time. It has no place in any new TV broadcasting standard.

APPENDIX

CEC RACE/HAMLET Deliverable no R2110/WP2/DS/R/013/b1

Recommendation on the Strategy of Using the Different Scanning Formats

Stephane Pigeon (UCL) - Philippe Guillotel (Thomson Multimedia R&D)

December 1995

The work performed within the framework of the RACE 2110 HAMLET Extension on Scanning Formats, leads to the following statements :

1. Interlaced format has been chosen in the early years of television considering it was one of the most interesting solution to achieve compression with regard to the available technology [1].

2. The improved quality of today's television sources and displays make the viewers less tolerant of the defects of the interlaced format (i.e. interline flicker, line crawling and field aliasing), especially for large displays, close viewing distance and high brightness levels [1].

3. Besides the typical interlaced defects, interlaced sources further suffer from a loss of vertical definition, deliberately introduced in order to reduce interline flicker [1].

4. With the change from analog to digital television, drastic changes will occur in our television system. These changes may be seen as a unique opportunity to change formats, implying only minor costs compared to the overall budget involved in such operation [1].

5. Leaving space for the future, it could be envisaged as a wise step not to degrade the image quality at the very beginning of the television process (i.e. inside the camera), chosing a lossy scanning format [1].

6. The choice of a scanning format needs to be done with care in order to avoid backward and lateral compatibility problems that would become difficult to overcome in the future [1].

7. Compared to interlace, progressive-scan signals are more suitable for digital compression in terms of high correlation for vertical and temporal directions, motion estimation and compensation [1].

8. Progressive scanning cameras suffer from a substantial signal-to-noise ratio loss due to the increased scanning velocity. However it can be

observed how the technological gap between interlaced and progressive is reduced passing from tube to CCD technology. A specific design of a CCD video camera for progressive scanning allows to increase significantly its performances with a cost comparable to that of interlaced [1].

9. Progressive frame-transfer CCD cameras allow to shot frames like a photograph and thus improves the display of still pictures taken from sequences that suffer from fast motion [1].

10. A progressive format offers the compatibility with computer graphics, multimedia applications and film production [1].

11. A progressive scanning format makes most signal processing operations easier than interlaced scanning, but since the system has to work with a doubled clock frequency and higher memory requirement in some cases, attention must be paid to the real complexity [1] :
    - Filtering. Vertical is intrinsically more effective for a signal sampled on a progressive grid, in terms of both complexity and final results.
    - Multi-resolution - HDTV/TV Scalability. Since interlaced performs poorly in terms of separation of the vertical frequencies, an intermediate progressive conversion is often considered even for interlaced-to-interlaced spatial scalability .
    - Frame Rate Conversions. Besides the 50/59.94/60Hz conversions (European/Japa-nese/American standards) which can be performed by handling interlaced fields only (to the detriment of some jerkiness), other conversions like 50/100Hz (improved domestic video displays) or 50/72Hz (compatibility with the computer world) require the use of a deinterlacer in order to offer a satisfactory quality.
    - Slow-motion. In order to avoid undesirable jerky motion effects specific to the simple field repetition, efficient slow motion algorithms are all based on high-quality deinterlacers.
    - Still Picture. Unlike a progressive format, still pictures taken from interlaced sources requires the use of motion compensation in order to avoid the loss of definition that occurs when performing still field display.
    - Aspect Ratio Conversion. Digital television will probably start in 16/9, so the problem of compatibility with 4/3 material is real. The required resampling reverts principally to a filtering problem (see above).
    - Chroma-keying. Digital chroma-keying is intended to replace the historical analog blue component-based process. Within the research currently under development, progressive material is

considered.

12. Besides the cathodic ray tube that takes benefit from the use of an interlaced format, new promising technologies like Active Matrix LCD, Digital Micromirror Device and Plasma Display Panel require a progressive input format [1].

13. With the advent of digital television, the uselessness of interlaced scanning will raise since digital coding offers many other ways to save bandwidth. Moreover, the use of a progressive format improves the subjective quality of the decoded sequences compared to an interlaced coding scheme. This result holds even in case of interlaced displaying of the progressive decoded sequence. [3][1].

14. Moving towards a progressive transmission scheme will require progressive-to-interlaced (low-cost) and interlaced-to-progressive (high-cost) conversions in order to manage pre-sent studio and consumer environments. Economical considerations will force the market to use low-cost conversions at the consumer side. Fortunately, if a progressive transmission scheme is adopted, only a progressive-to-interlaced conversion must be carried at this side in order to ensure the compatibility with old interlaced displays. This conversion can easily be integrated in the digital decoder that will be purchased if an analog interlaced display is used to decode digital broadcast services.
    Interlaced studios will have to make use of a high-cost deinterlacer. Besides removing the interlaced artifacts, this deinterlacer is supposed to improve the digital coding of interlaced sources [3]. However, this result holds for high-quality deinterlacers only and has to be achieved by the use of a finely tuned motion estimation and compensation. Also, field aliasing has to be handled properly. The general sampling theory offers such requirements. A deinterlaced based on such technique has been described in [2].

15. Work carried in WP2, comparing CCIR 601 interlace with a 50Hz-progressive scanning format, showed that [3]:
    - *if an all progressive chain is compared to an all interlaced one (same bit-rate), progressive is generally preferred to interlaced mainly due to the display; (emphasis added)*
    - if interlaced display is used, progressive transmission improves the picture quality if progressive sources are used. The degree of improvement is linked to the complexity of the source material (higher the complexity, bigger the improvement). Conclusions are not as clear when dealing with interlaced sources since the results depend on the quality of the deinterlacer and the contents

of the source sequence. In general, similar results are performed (but at higher cost for progressive since the prior deinterlacing operation and the doubled clock speed).

16. 50Hz-Progressive transmission leads to more stable bit-rate control and offers a more homogeneous picture quality [3].

As a conclusion, *when considering the same bit-rate,* (emphasis added) an all progressive broadcasting chain (from the source capture to the final display) is preferable to an all interlaced one, except for the increased hardware performance since twice the number of pixels have to be scanned. A progressive chain offers an improved picture quality, a more homogeneous transmission quality and the compatibility with multimedia applications (computer, film, digital processing,...). However, a progressive coding can not be seen as an efficient way to improve the quality of the decoded sequence, as long as interlaced displays are concerned, but can be used as an intermediate step towards a fully progressive television implementation without loss of performance compared to the existing interlaced format. Moreover, the choice of a progressive scanning format for the future digital television should not be regarded as an efficient way to improve quality but as a wise step towards multimedia and computer compatibility.

For such reasons, a progressive format has already been considered for the introduction of the new digital television services in the U.S. and Japan. In a European context, the adoption of a progressive scanning format will have to cope with the decision of the DVB group, which expressed itself in favour of the MP@ML MPEG2 coding scheme. Just as it is, MP@ML does not allow the coding of 50Hz-progressive sequences. However, this limitation only comes from the definition of the MP@ML itself which was decided to restrict the pixel rate below that needed by a 50Hz-progressive format. From a practical point of view, this problem is meaningless since the 50Hz-progressive format may be coded using the same bit rate as interlaced at same or improved visual quality. In other words, it would have been more judicious defining the MP@ML to include the 50Hz-progressive format. On the contrary, the 50Hz-progressive format has been classified with other high-cost formats that require a more complex high-1440 level-compliant decoder (MP@H-14). As proposed by the RACE Image Communication Project Line, this syntax problem can be solved by defining an intermediate MPEG2 level compatible with the 50Hz-progressive format. However, this demand could take a long time before being considered by the MPEG2 authorities. Moreover, the moderate improvements offered by a progressive transmission scheme are not eager to boost alone such a demand. As it is difficult to propose a new profile, it is suggested to cope with existing ones (MP@ML or professional 4/2/2) with either lower picture size or frame rate for the progressive format. In these cases simulations are required to evaluate the impact of using different spatial or temporal resolution, but results from the Grand Alliance are promising.

Finally note that a 25Hz-progressive scanning format is already compatible with the

MP@ML considered by the DVB group. Thus, it is proposed to use this format for the encoding of films (24Hz-progressive), which represent an important source of motion picture material for future television apart from video-camera sources. Hence, the choice will be given to the display to keep the progressive source or convert it into interlace, depending on the quality to be offered to the consumer.

References :

1 S. Pigeon and P. Guillotel, "Advantages and Drawbacks of Interlaced and Progressive Scanning Formats ", CEC RACE/HAMLET Deliverable no R2110/ WP2/DS/R/004/b1, June 1995.

2 S. Pigeon, L. Vandendorpe, L. Cuvelier and B. Maison, " Specification of a Generic Format Converter", CEC RACE/HAMLET Deliverable no R2110/WP2/DS/S/006/b1, September 1995.

3 P. Guillotel and S. Pigeon, "Coding Efficiency Comparisons of both Interlaced and Progressive Scanning Formats", CEC RACE/HAMLET Deliverable no R2110/WP2/DS/S/012/b1, December 1995.

The Progressive/Interlace (P/I) Issue

I have received a number of comments about my recent submissions to the FCC on this matter. While most have been favorable, there are still skeptics who think that interlace has some value in some cases.

Please note that my argument does not depend on the recent remarkable finding that a P and an I video signal with an equal number of lines per frame and an equal number of fields per second, the P signal having twice the analog bandwidth of the I signal, can be MPEG-coded in the same number of bits/sec. This has now been reported by NHK, RAI, and CCETT. The papers describing these results were included with my submissions and are available by sending a request to dmanning@image.mit.edu. Attached to this note is a new paper from Norway showing that, using properly optimized MPEG coding at the same data rate, a 576x1024x50 P picture is subjectively superior to an 1152x1024x25 I picture.

There was plenty of evidence that P was better than I even without this new information. For example, in the recent ATTC tests, a 720-line P picture was compared with a 1080-line I picture. In this case, the uncoded date rates and therefore the analog bandwidths were about the same. The subjective quality of the P picture was the same as the subjective quality of the I picture, and the measured vertical resolution of the P picture was higher. This was so in spite of the fact that the 720 P signal, being derived from 1125 I, did not exploit the higher vertical resolution capabilities of the 720 P system.

As I have often stated, interlace can be thought of, equivalently, as an attempt to double the vertical resolution at a given number of lines/sec, or to double the large-area flicker rate without losing vertical resolution. It has been known at least since 1966 that the actual increase in vertical resolution under typical conditions of brightness and line number is no more than 10%. The main favorable effect of interlace seems to be a slight reduction in the visibility of line structure, which can be seen only in low-resolution systems. On the other hand, there are many unfavorable effects that I and others have commented upon many times.

The final nail in the coffin of interlace was the development of the Polaroid P camera. This camera, the development of which was said by I enthusiasts to be many years away, produces superb pictures and its sensitivity is fully adequate for all HDTV applications. Since it uses the very first 720x1280 chip made by Polaroid, we can be sure that later models will be even better. It is a fully engineered camera, available for sale today. *Interlace is now obsolete.*

These considerations fully support the conclusions of my several FCC submissions. There is no advantage for any domestic stakeholder in the use of interlace in any new digital transmission format; on the contrary, many roadblocks are placed in the path of ATV development by permitting its use. Unfortunately, a number of foreign-owned manufacturers have made investments in this obsolete technology, and are now pushing for the use of interlace. There is no reason at all for the United States to select a domestic ATV standard except to further the interests of domestic stakeholders. On that basis, progressive wins, hands down.

William F. Schreiber 21 August 1996 wfs@image.mit.edu 617 253 2579

A Comparison of Different Coding Formats for Digital Coding of Video Using MPEG-2

Gisle Bjøntegaard, Karl Olav Lillevold, and Robert Danielsen

***Abstract*— This correspondence adresses the problem of maximizing the subjective picture quality at given bit rates for coded video. Coding is carried out using different picture formats. The parameters involved are the number of pixels horizontally and vertically and interlacing/noninterlacing. The coding is done according to the MPEG-2 standard.**

I. Introduction

The MPEG-1 and MPEG-2 [1], [2] coding methods for video compression belong to a class of methods referred to as *hybrid discrete cosine transform (DCT)*. The ITU H.261 and H.263 Recommendations also belong to this class. These methods are well documented elsewhere and will therefore not be introduced in detail here. We will focus only on the aspects of special importance for this work.

The MPEG methods are largely based on dividing the picture material into 16 × 16 blocks of picture material (macroblocks). For each of these blocks there is a prediction block, which is found in previously decoded pictures by using displacement vectors. In some cases the prediction is sufficient to represent the 16 × 16 pixels. However, most of the time a difference block has to be transmitted. For the 16 × 16 block, a difference block is produced by subtracting the prediction from the block to be coded. The difference block undergoes a two-dimensional 8 × 8 DCT. The transform coefficients are then quantized before being entered into a bitstream. The quantization parameter Q determines the level of quantization; we may view this as the "coarseness" of the resulting picture. The parameter Q referred to in this work is the actual divisor used for quantization. To a large extent the size of Q therefore determines the number of bits produced from a 16 × 16 block. The resulting number of bits can be considered to consist of two parts: i) motion vector data for prediction plus general overhead and ii) transform coefficients.

The transform coefficients usually account for the largest part. The number of bits used for transform coefficients is influenced by the size of Q and may therefore directly be controlled by the rate control mechanism employed. The rate control mechanism uses a buffer fullness measure to give feedback to the adjustment of Q.

In this correspondence, a format or picture format is defined by the horizontal and vertical pixels in a picture as well as the interlaced or progressive structure of pixels (see Figs. 1, 2, and 3). We will talk about interlaced and progressive formats. We will also talk about low-resolution formats and high-resolution formats indicating whether a format has few or many pixels.

The MPEG standard does not give detailed rules of how pictures shall be coded. The standard is, rather, a protocol for the decoding procedure. Another way to see this is that MPEG provides a toolbox that may be used by the encoder to obtain good compression performance. This means that many choices are left for the encoder. The present paper examines the combination of three important

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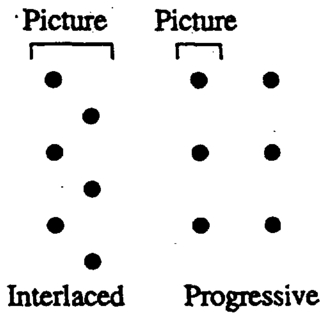

Fig. 1. Interlaced and progressive TV formats.

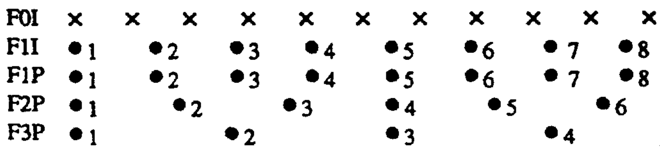

Fig. 2. Horizontal pixel positions for the different formats.

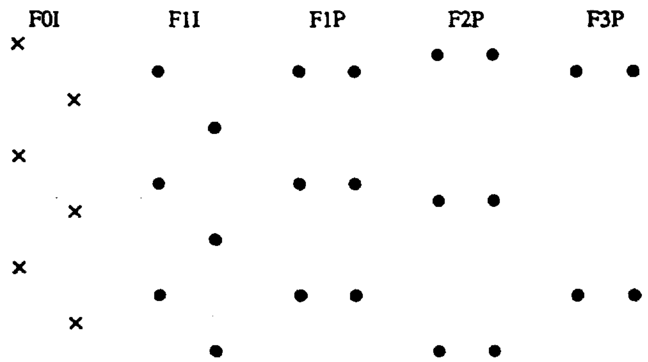

Fig. 3. Vertical pixel positions for the different formats.

parameters: produced bit rate, picture format (measured in number of pixels), and quantization parameter (Q).

The first experiment concerns the use of interlaced or noninterlaced (progressive) picture format. The picture format normally used for TV purposes is called *interlaced.* An interlaced picture (a frame) can be regarded as two separate "fields" with half the number of vertical lines, as indicated in Fig. 1. The lines in each field are shifted relative to each other. A format without this line shift is called *progressive.* This is also shown in Fig. 1. Progressive formats are normally used in all applications except TV. The MPEG-1 standard is aimed at coding progressive formats only. The MPEG-2 standard includes tools for coding both interlaced and progressive material. For progressive material the coding method in MPEG-2 is nearly the same as in MPEG-1. A comparison of MPEG-1 and MPEG-2 on pure interlaced material is given in [3].

The second and main experiment examines the parameters described above (bit rate, format, and Q) for progressive formats. An important aspect of coded digital video is that there is no longer a direct relationship between picture quality and the number of pixels in a picture. We know that for noncompressed digital video, the image quality increases in steps when going from a low format like CIF [4] to CCIR-601 [5] to HDTV formats. But for compressed video, the picture quality depends on both coding format and Q. The coding format gives an upper limit to obtainable picture quality. This work will try to investigate the relationship among subjective quality, bit rate, and picture-coding format. The progressive format in three different resolutions will be used for this purpose.

TABLE I
CODING FORMATS

Format	Horizontal pixels	Vertical lines	Pict. frequency	Horizontal conversion	Vertical conversion
F0I	1440	1152	25Hz		
F1I	1024	1152	25Hz	1408→1024	1152→1152
F1P	1024	576	50Hz	1408→1024	1152→576
F2P	768	432	50Hz	1408→768	1152→432
F3P	512	288	50Hz	1408→512	1152→288

II. Picture Material And Formats

Two digital video sequences were used for the present test: Ski and Crowd. Ski depicts a cross-country skier with spectators on both sides. The camera pans as it follows the skier along the ski slope. Crowd depicts a large crowd of people at a tennis tournament. This sequence has a slow panning camera motion, with some additional motion from the spectators. Both these sequences are intended for use in HDTV testing in Europe. The picture sequences were recorded in interlaced format F0I defined in Table I. The camera had an aspect ratio (relation between horizontal and vertical size) of 16:9. From this format several other formats with different numbers of pixels were derived for testing. These will be named *coding formats.* F0I is of type 4:2:2, meaning that the horizontal number of chrominance pixels is half that of luminance. The vertical number of chrominance lines is the same as for luminance. All the derived formats are of type 4:2:0, which means that the number of chrominance pixels is half that of luminance vertically as well as horizontally. 4:2:0 is the format used in the MPEG-2 Main Profile.

All the coding formats are intended for display on a screen with aspect ratio 16:9. The coding formats have *square pixels,* which means that the ratio between numbers of horizontal and vertical pixels is the same as the aspect ratio.

The formats F1I and F1P are used for comparing coding of interlaced and progressive material. The pixels in those two formats have been constructed in such a way that the information content should be very similar using the two formats. They represent the same number of pixels per second. The down-filtering is also done so that the information content should be very similar. The formats F1P, F2P, and F3P are all progressive formats with different numbers of pixels. They will be used for comparing subjective quality versus bit rate with different picture resolutions. Fig. 2 shows the luminance horizontal pixel positions, while Fig. 3 shows the luminance vertical pixel positions of the different formats.

The filters used to derive the coding formats were designed to preserve as much of the information content as possible without giving noticeable aliasing or ringing effects. Tables II and III give the filter taps used to produce the horizontal and vertical down-sampling for the different formats. Notice that the vertical filter taps that produce F1I and F1P are identical. This means that the information content of the two formats are close to equal.

III. Test Conditions

The subjective tests in this paper were conducted using the Double Stimulus Continuous Quality Scale (DSCQS) method described in CCIR Rec. 500-5 [6]. This means that each coded sequence was shown together with a reference sequence. The observers were not

TABLE II
HORIZONTAL FILTER TAPS FOR DOWN-SAMPLING TO THE CODING FORMATS

Pel no.	F0I → F1I,P	F0I → F2P	F0I → F3P
1	(2,28,2)/32	(-1,5,24,5,-1)/32	(-3,2,19,28,19,2,-3)/64
2	(-3,23,14,-2)/32	(-2,9,23,2)/32	(-3,5,23,27,14,-2)/64
3	(-1,9,26,-2)/32	(-2,13,21)/32	(-1,-2,9,26,26,9,-2,-1)/64
4	(27,5)/32	(-1,17,17,-1)/32	(-2,0,14,27,23,5,-3)/64
5	(-3,19,19,-3)/32	(21,13,-2)/32	
6	(5,27)/32	(2,23,9,-2)/32	
7	(-2,26,9,-1)/32		
8	(-2,14,23,-3)/32		

TABLE III
VERTICAL FILTER TAPS FOR DOWN-SAMPLING TO THE CODING FORMATS

	Pel no. 1	Pel no. 2	Pel no. 3
F0I → F1I	(-1,24,10,-1)/32		
F0I(fi.0) → F1P	(-1,24,10,-1)/32		
F0I(fi.1) → F1P	(-1,10,24,-1)/32		
F0I(fi.0) → F2P	(-1,5,24,5,-1)/32	(21,13,-2)/32	(-2,13,21)/32
F0I(fi.1) → F2P	(-1,17,17,-1)/32	(-2,9,23,2)/32	(2,23,9,-2)
F0I(fi.0) → F3P	(-2,0,14,27,23,5,-3)/64		
F0I(fi.1) → F3P	(-3,5,23,27,14,0,-2)/64		

told which one was the reference, and the position of the reference was changed in a pseudorandom fashion. The inclusion of a reference avoids a gradual change in the observers' assessments during the test. Each particular test sequence was shown at least twice during the session.

The observers were asked to assess the overall quality of each presentation by inserting a mark on a vertical line. The vertical lines were printed in pairs to accommodate the double presentation of each test sequence. The lines provided a nearly continuous rating system to avoid large quantizing errors, but they were divided into five equal lengths that corresponded to the scales: *Excellent, Good, Fair, Poor,* and *Bad*. After assessment, the vertical lines were scaled from zero to 100, and the number corresponding to each vertical mark was registered. For each sequence and each observer, the mean score of the reference sequence was calculated. This served as a reference score for each sequence. From this reference score, the score for each coded sequence was subtracted. The resulting number is a measure for the degradation compared to the reference, and is called the *degradation value.*

For each of the subjective tests, we used 15 observers. The coherence of the results was checked by examining the grades given by the same observer to both occurrences of the same sequence in each session. If the gradings differed with more than 20 points on the continuous scale, both scores were eliminated. To give the assessor some time to see the range of quality, the results of a few "dummy" sequences shown first were always discarded.

For a given sequence, we therefore obtain N degradation values D_n. From these numbers we calculate the mean and the standard deviation.

The mean is as follows:

$$\bar{D} = \frac{\sum_1^N D_n}{N}.$$

The standard deviation is as follows:

$$\sqrt{\frac{\sum_1^N (D - \bar{D})^2}{N}}.$$

All sequences were displayed on a SONY HDM-2830E HD monitor with a 27-in screen. The interlaced sequences were displayed as 1024×1152×25Hz interlace, whereas the progressive formats were displayed as 1024×576×50Hz progressive. For the formats F2P and F3P, it was therefore necessary to do vertical up-conversion to produce 576 lines. The horizontal number of pixels were displayed directly with appropriate analog filters after D/A conversion by the imaging system.

The sequences were all coded using an implementation of the test model TM4 [7] in the MPEG-2 work. We always used two interpolated frames in between each predicted frame. For the interlaced sequences at 25 Hz, we used a distance of 12 frames between each intraframe, while the progressive sequences at 50 Hz were coded using a distance of 24 frames between each intraframe. In the motion vector search, we used a search window that was large enough to contain the real motion in each of the sequences. The physical size of the search window was the same in all cases, i.e., the size in number of pixels varied. This window was always quite small considering the moderate amount of motion in these sequences. A list of MPEG-specific parameters is given in the Appendix.

IV. INTERLACED VERSUS PROGRESSIVE

The interlaced format has some benefits for analog TV. It gives high vertical resolution for nonmoving pictures and high temporal resolution for moving pictures. For moving sequences, though, there may be artefacts due to aliasing when interlacing is used. Altogether, the use of interlaced format seems beneficial in a noncompressed system.

MPEG-2 includes tools for handling interlaced pictures. Each interlaced picture is divided into two fields (Fig. 1), and both prediction and transformation may be made field- or picture-oriented. These decisions may be made on the block level. Despite this, the nonregular sampling structure of the interlaced format can result in less efficient coding. This is due to the fact that the prediction may be poorer because of interpolation between lines farther apart than they would be in a progressive system. Transformation may also be less efficient because lines in the transform are farther apart and therefore less correlated.

For this work, we have produced interlaced and progressive formats with exactly the same number of pixels/second. We assessed the downsampled pictures produced before any coding, and our impressions may be summarized as follows.

- There was some visible degradation in sharpness between F0I and F1I. However, the degradation was considered to be small. This partly reflects the limitations in the monitor.
- The quality of F1P (displayed as progressive) and F1I (displayed as interlaced) were identical. No difference could be seen.
- No difference due to the interlaced and progressive displays was noticed. This may partly be due to the vertical lowpass filtering in the conversion. On the other hand, very little interlace distortion was noticed even when displaying the original F0I as interlaced.

Therefore, it is our opinion that the test results in this work reflect the difference in coding efficiency when using interlaced and progressive coding formats. Particularly, it reflects the level of quality one can expect when using the tools for handling interlaced material in MPEG-2.

TABLE IV
MEAN DEGRADATION AND STANDARD DEVIATION FOR INTERLACED AND PROGRESSIVE FORMATS

Sequence		SKI			CROWD	
Bitrate		7 Mb/s	10 Mb/s	13 Mb/s	8Mb/s	12Mb/s
Interlaced	Mean degradation	46	27	16	50	40
	Standard deviation	13	12	8	18	14
Progressive	Mean degradation	27	14	11	37	32
	Standard deviation	14	9	10	16	14

TABLE V
LUMINANCE SNR AND MEAN QUANTIZER FOR INTERLACED AND PROGRESSIVE FORMATS

Sequence		SKI			CROWD	
Bitrate		7 Mb/s	10 Mb/s	13 Mb/s	8Mb/s	12Mb/s
Interlaced	SNR [dB]	32.2	34.0	35.0	30.1	31.9
	Mean Q	20.4	12.8	9.6	21.2	14.0
Progressive	SNR [dB]	33.9	35.0	35.9	30.8	32.3
	Mean Q	12.4	9.4	7.8	15.8	11.4

V. EXPERIMENT 1: COMPARISON OF INTERLACED AND PROGRESSIVE FORMATS

The sequence Ski was coded at 7, 10, and 13 mb/s and Crowd was coded at 8 and 12 mb/s. The results of the subjective tests are shown in Table IX. Both mean degradation and standard deviation are given. Luminance signal-to-noise ratio (SNR) and mean quantizer from the simulations are given in Table V. The mean values of the subjective scores are plotted in Fig. 4.

The results show that the progressive sequences in all cases get a lower degradation value than the corresponding interlaced sequences. From the curves in Fig. 4, we see that the interlaced version of Ski needs about 40% more bits to achieve the same subjective quality as the progressive version. The corresponding number for Crowd can be extrapolated to being around 60%.

These results confirm that for moving sequences, progressive formats perform better than interlaced formats when they have the same number of pixels per second. For the purpose of digital video coding, a progressive format of 1024 × 576 (50 frames/s) is preferable to an interlaced format of 1024 × 1152 (25 frames/s).

VI. A MODEL FOR SUBJECTIVE QUALITY VERSUS BIT RATE

The MPEG-2 standard defines a data syntax for compressed video. This is related to specific tools for compression. Following the standard does not guarantee a good resulting picture quality. This will depend on several factors that include the following:

1) image content: the amount of high spatial frequency information and motion in the sequence;
2) picture-coding format (number of coded pixels per second);
3) number of bits transmitted per second
4) How much of the sequence is coded without prediction (intra-coded);
5) the number of MPEG-2 coding tools used;
6) cleverness in using the coding tools, especially the motion vector search.

The picture quality will vary considerably depending on the above choices/parameters. In this section, we will focus on the relationship between subjective picture quality, bit rate, and picture-coding format.

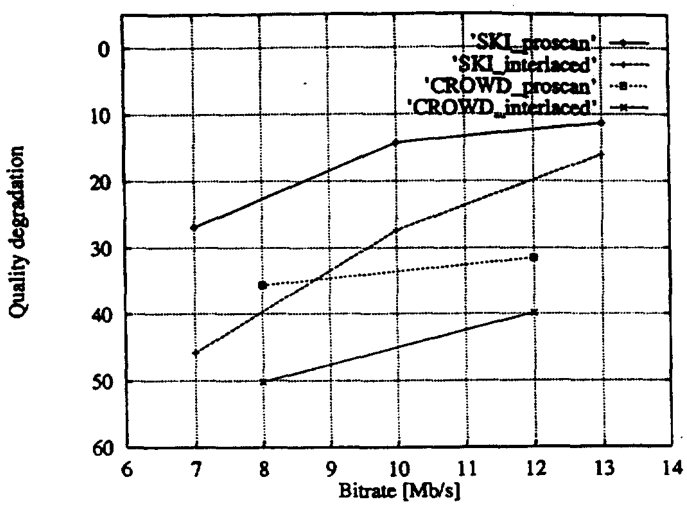

Fig. 4. Subjective test: Interlaced versus progressive for Ski and Crowd.

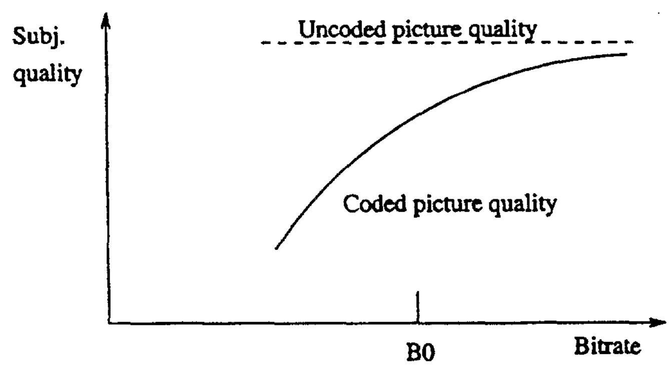

Fig. 5. Normal curve for subjective quality versus bit rate.

Assume that the parameters above (1)–(6) are constant except bit rate (3). The relationship between subjective quality and bit rate will then typically be as shown in Fig. 5. As the bit rate increases (by means of reducing the quantization parameter Q), the quality approaches the quality of the uncoded picture. Fig. 5 illustrates how the cost in bit rate of obtaining additional quality becomes rather high as we approach the uncoded quality.

At the lower end, the curve will have a practical limit. As mentioned above, the quantization parameter only controls the part of the total bit rate generated by transform coefficients. Bits used for prediction vectors and overhead are more or less constant and related to picture material and coding format. When these bits occupy a majority of the total bit rate available, the overall rate control does not work properly. This explains why there is a lower "useful limit" on the curve and why the curve does not drop to "zero subjective quality."

If we use a lower format with fewer pixels per second, a given bit rate will provide more bits per pixel in the coding process. On the other hand, a larger format means a higher maximum quality. A higher format also tends to give less visible blocking artifacts due to smaller blocks and better prediction due to a finer grid.

We may now ask the questions: What is the relationship between quality and bit rate if we use a different picture format? At what bit rates is this other format preferable to the format assumed in Fig. 5? At a given bit rate B0, what would be the optimal coding format for obtaining maximum subjective picture quality?

We have therefore measured subjective quality versus bit rate for three different coding formats. Such measurements will give an answer to the question raised above.

TABLE VI
MEAN DEGRADATION AND STANDARD DEVIATION AT FORMAT F1P (1024 × 576)

Sequence	SKI			CROWD		
Bitrate	5Mb/s	9Mb/s	13Mb/s	7Mb/s	12Mb/s	16Mb/s
Mean degradation	14	0	-6	26	9	1
Standard deviation	12	13	13	9	14	12

TABLE VII
MEAN DEGRADATION AND STANDARD DEVIATION AT FORMAT F2P (768 × 432)

Sequence	SKI				CROWD			
Bitrate	3Mb/s	6Mb/s	9Mb/s	15Mb/s	5Mb/s	8Mb/s	12Mb/s	17Mb/s
Mean degradation	39	26	16	10	46	28	17	15
Standard deviation	12	11	11	12	11	10	13	13

TABLE VIII
MEAN DEGRADATION AND STANDARD DEVIATION AT FORMAT F3P (512 × 288)

Sequence	SKI				CROWD			
Bitrate	2Mb/s	4Mb/s	7Mb/s	12Mb/s	4Mb/s	6Mb/s	9Mb/s	14Mb/s
Mean degradation	51	45	39	34	62	56	47	42
Standard deviation	10	10	9	12	8	9	10	10

TABLE IX
SNR AND MEAN QUANTIZER AT FORMAT F1P (1024 × 576)

Sequence	SKI			CROWD		
Bitrate	5Mb/s	9Mb/s	13Mb/s	7Mb/s	12Mb/s	16Mb/s
SNR [dB]	32.4	34.3	35.5	29.5	31.5	32.7
Mean Q	16.8	9.8	7.4	19.8	12.2	9.8

TABLE X
SNR AND MEAN QUANTIZER AT FORMAT F2P (768 × 432)

Sequence	SKI				CROWD			
Bitrate	3Mb/s	6Mb/s	9Mb/s	15Mb/s	5Mb/s	8Mb/s	12Mb/s	17Mb/s
SNR [dB]	30.9	33.4	34.8	36.5	28.7	30.6	32.3	33.9
Mean Q	18.8	10.0	7.2	4.8	18.4	12.4	9.0	6.8

TABLE XI
SNR AND MEAN QUANTIZER AT FORMAT F3P (512 × 288)

Sequence	SKI				CROWD			
Bitrate	2Mb/s	4Mb/s	7Mb/s	12Mb/s	4Mb/s	6Mb/s	9Mb/s	14Mb/s
SNR [dB]	31.1	33.9	36.2	38.3	30.4	32.2	34.0	36.0
Mean Q	14.6	8.2	5.0	3.2	11.6	8.6	6.0	4.2

VII. EXPERIMENT 2: QUALITY VERSUS BIT RATE FOR DIFFERENT PICTURE FORMATS

For each of the coding formats, the test sequences were coded at different bit rates. The objective of the experiment was to measure the subjective quality depending on both bit rate and picture resolution.

The subjective test was performed as described in Section III. The ·erence sequence was the uncoded F2P format throughout the test. Tables VI–VIII give the results of the subjective tests at the different bit rates and resolutions. Tables IX–XI give the objective results from the simulations. The mean values of quality degradation from the subjective tests are plotted in Figs. 6 and 7.

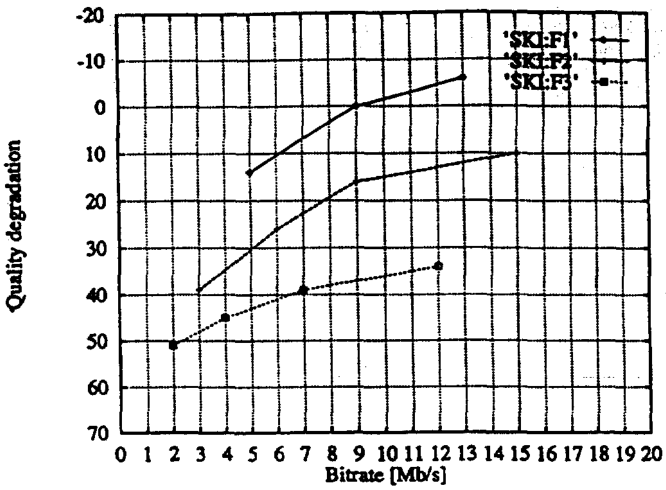

Fig. 6. Subjective test: quality versus bit rate for Ski.

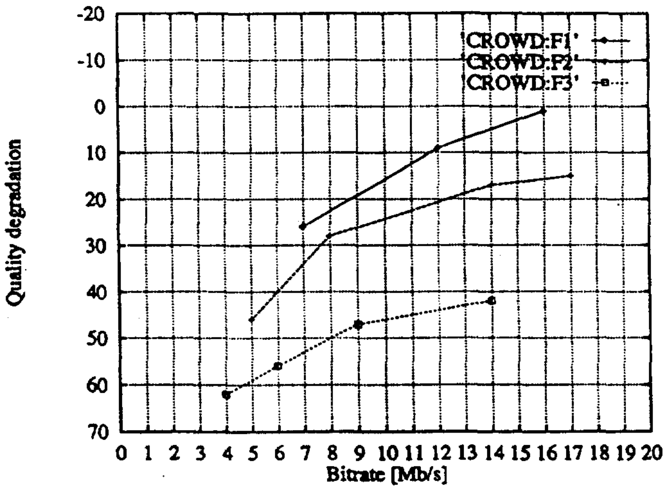

Fig. 7. Subjective test: quality versus bit rate for Crowd.

Some interesting observations can be made from Fig. 6 and Fig. 7. We refer back to Fig. 5 as the model for subjective quality versus bit rate. Figs. 6 and 7 represent several such measured curves. It is seen that these curves never cross each other. For all bit rates and formats tested, the same bit rate at a lower format would have resulted in reduced subjective quality.

For formats F1P and F2P, the mean value of Q for the lowest bit rates tested was in the range 17–20. The subjective quality at these lowest bit rates is still well above the subjective quality for the same bit rate but with a lower format. This indicates that for a given bit rate, maximum subjective quality is obtained if coding picture format is chosen in such a way that the resulting mean Q is somewhat higher than 20.

The lowest bit rate for each format was chosen before the test. These lowest bit rates resulted in clearly visible artifacts.

VIII. CONCLUSIONS

In the present work we have carried out subjective assessments of video quality for MPEG-2 coded video sequences. The assessment method has been the Double Stimulus Continuous Quality Scale (DSCQS) described in CCIR Rec. 500-5. The coding method has been MPEG-2 with two interpolated frames between each predicted frame.

It was found that the progressive sequences showed better subjective quality than the corresponding interlaced sequences. It was estimated that the interlaced sequences needed around 50% more bits to obtain the same subjective score as the progressive sequences.

The other comparison was on subjective quality with different picture-coding formats. In our tests, the highest format always came out best. For the two sequences tested here, the MPEG-2 coding algorithm seems to work best for formats that result in quantization parameters somewhat higher than 20.

Appendix

Some important MPEG-specific coding parameters used in these experiments are listed below.

- Coding structure:
  - $M = 3$ for all experiments
  - $N = 12$ for interlaced sequences, i.e. sgIBBPBBPBBPgBBIBB..., where s is sequence header, g is group header, I is intra frame, B is bidirectionally predicted frame and P is predicted frame.
  - $N = 24$ for progressive sequences
- Quantization:
  - q_scale_type = 0, which means that the value of Q is the actual divisor used. Q is in the range 2, 4, 6, . . . ,60, 62.
  - The quantization matrices from TM4 [7] were used.
- All progressive sequences were coded in MPEG-1 mode, i.e., using only frame prediction and frame DCT.
- Miscellaneous:
  - alternate_scan = 0.
  - intra_vlc_format = 1.
  - intra_DC_precision is 8 b.

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